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Axion Decay of a 17-keV Neutrino

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A 17-keV particle tentatively observed in β decays is assumed to be a new Dirac-type neutrino. Coupling to the Higgs sector of the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) axion model provides a mass for this particle, its mixing with the electron neutrino, and a channel for a reasonably fast decay into an electron neutrino and the light DFSZ axion. Results are consistent with most laboratory, astrophysical, and cosmological limits on the properties of this particle and of the axion.

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Over the past several years tentative evidence has appeared in nuclear β decay for the existence of a 17-keV neutrino [1-3]. Approximately 1% of the decays produce this new particle [2,3], which we shall call ν_H. Although it is simple to envisage schemes where the ordinary electron neutrino mixes with the ν_H, where ν_H is either one of the known neutrino species or a new type, laboratory experiments and astrophysical and cosmological considerations put constraints on the properties of this particle. One of the tightest is the requirement that the lifetime of ν_H be less than 10^{14} s [4], in order to prevent an "overclosure" of the Universe. This limit was used as a guide in the formulation of this model; constraints from primordial nucleosynthesis and from observations on the supernova 1987A will be discussed, as will be those from terrestrial observations. Recently two proposals have appeared to account for this particle; Glashow [5] took the ν_H to be a Majorana particle whose primary decay is into a light neutrino and a majoron, while Babu, Mohapatra, and Rothstein [6] considered it to be a Dirac neutrino whose right-handed component has new couplings, permitting a fast decay into three light neutrinos.

In this Letter we propose that ν_H is a *new, $SU(2)_L$-singlet, Dirac* neutrino that obtains its mass and mixes with ν_e through the Higgs mechanism of the Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) [7,8] "invisible" axion scheme. The primary decay of ν_H is into ν_e and an axion; the lifetime for this decay is $\sim 10^{12}$ s, within the allowed cosmological limit.

The Higgs sector of the DFSZ model consists of two doublets h_1 and h_2 with vacuum expectation values v_1 and v_2, respectively, and a singlet χ with a much larger expectation value u. The Yukawa Lagrangian has two parts, $\mathcal{L}_{Y1}$, the usual couplings of the Higgs particles to quarks and leptons, and an additional part involving the ν_H, $\mathcal{L}_{Y2}$:

$$\begin{aligned}\mathcal{L}_{Y1}&=\sum_i\left(\frac{m_i^{(d)}}{v_1}\bar{q}_{Li}h_1 d_{Ri}+\frac{m_i^{(u)}}{v_2}\bar{q}_{Li}\tilde{h}_2 u_{Ri}+\frac{m_i^{(e)}}{v_1}\bar{l}_{Li}h_1 e_{Ri}\right)+\text{H.c.}\,,\\ \mathcal{L}_{Y2}&=\frac{m_{\nu_H}}{u}\nu_{HL}\chi\nu_{HR}+\frac{\xi_{\nu_e}m_{\nu_H}}{v_2}\bar{l}_{eL}\tilde{h}_2\nu_{HR}+\text{H.c.}\end{aligned} \tag{1}$$

u_i, d_i, e_i, and ν_i denote the upper and lower components of the quarks and leptons in generation i. ξ_{ν_e} is the amount of mixing of ν_H with ν_e; according to the experiments [2,3] $\xi_{\nu_e}\approx 0.1$. The light neutrinos remain massless and the linear combination of states that couples to both charged and neutral currents is $|\nu_e\rangle+\xi_{\nu_e}|\nu_H\rangle$. In the above Lagrangian the new heavy neutrino is coupled only to the electron family. Extra heavy neutrinos coupling to the other families could be introduced, or we could allow ν_H to couple to the other lepton families. We shall return to these topics towards the end of this Letter. This Lagrangian is invariant under a U(1) symmetry with Peccei-Quinn charges

$$\begin{aligned}&Q(u_{iR})=b,\ \ Q(d_{iR})=c,\ \ Q(l_{iR})=c,\ \ Q(\nu_{HR})=b\,,\\ &Q(h_1)=-c,\ \ Q(h_2)=b,\ \ Q(\chi)=-(b+c)/2\,,\\ &Q(\nu_{HL})=(b-c)/2\,.\end{aligned} \tag{2}$$

The spectrum contains, of course, an axion a with decay constant

$$f_a=\frac{v(4v_1^2v_2^2+v^2u^2)^{1/2}}{2v_1v_2}\,, \tag{3}$$

where $v=(v_1^2+v_2^2)^{1/2}$. In addition to its usual couplings to quarks and leptons the axion couples to ν_H and ν_e,

$$\mathcal{L}_{\nu_H\nu_e a}=i\xi_{\nu_e}m_{\nu_H}\frac{v_1}{v_2 f_a}\bar{\nu}_{eL}\nu_{HR}a+\text{H.c.} \tag{4}$$

This leads to a lifetime for the decay $\nu_H\to\nu_e a$ of

$$\tau=\left(\frac{v_2 f_a}{v_1\xi_{\nu_e}}\right)^2\frac{32\pi}{m_{\nu_H}^3} \tag{5}$$

or

$$\tau = 1.35\times10^{8}\left(\frac{v_2}{v_1}\right)^{2}\left(\frac{f_a}{10^{7}\,\mathrm{GeV}}\right)^{2}\times\left(\frac{m_{\nu_H}}{17\,\mathrm{keV}}\right)^{-3}\left(\frac{\xi_{\nu_e}}{0.1}\right)^{-2}\mathrm{s}. \qquad (6)$$

Astrophysical considerations put constraints on the axion mass [9,10] and in turn on f_a. The evolution of red giants provided the most stringent stellar limit, $m_a < 0.02$ eV or $f_a > 3\times10^{8}$ GeV. The observed cooling rate of supernova 1987A tightened this limit to $m_a < 3\times10^{-3}$ eV or $f_a > 2\times10^{9}$ GeV. With v_2/v_1 in Eq. (6) of order unity, and $f_a = 10^{9}$ GeV we obtain $\tau \approx 10^{12}$ s, within this cosmological limit. (Theories of structure formation in the Universe place a more stringent limit on the particles decaying into relativistic daughters, namely, $\tau \le 6\times10^{6}$ s [11]. Should these ideas on structure formation hold, they would rule out this and other models for this particle.)

Primordial nucleosynthesis is used to place a limit on the number of neutrino types. A recent analysis [12] limits the number of species (neutrino plus antineutrino of one handedness) to be less than 3.4. Neutrinos that decouple very much earlier than the nucleosynthesis epoch contribute significantly less than 1 to this bound; this is the situation with the right-handed component of ν_H. The left-handed component of ν_H decouples only shortly prior to ordinary neutrino decoupling and thus contributes fully to the expansion rate of the Universe at the time of nucleosynthesis, seriously violating the above bound. However, a recent reanalysis of nucleosynthesis [13], which allowed for the possibility of a neutrino chemical potential, weakened the limit on the number of neutrinos considerably.

Astrophysical constraints come from a study of the cooling rates of the supernova 1987A. Cooling due to new quanta should not be so fast as to interfere with the observed neutrino fluxes. In order to prevent the "sterile" right-handed component of ordinary neutrinos from carrying away energy too rapidly, an upper limit of 14–17 keV [14] for the mass of such a particle was obtained. As ν_H interacts with a strength of $\xi_{\nu_e}G_F$, the limit on its mass from such considerations is 140–170 keV. The right-handed component of our 17-keV ν_H will not be produced at a rate sufficient to affect the evolution of a supernova. The left-handed component of ν_H has a mean free path $1/\xi_{\nu_e}^2$ or 100 times that of an ordinary neutrino. It will set up a ν_H-sphere and thermally radiate these particles. Details depend strongly on the density profile and equation of state of a supernova core. Following Grifols and Massó [15], we find that ν_{HL} radiates at a rate of $100^{22/32} \approx 24$ times that of an ordinary neutrino. For the parameters used in this analysis, the rate of ordinary neutrino radiation is 10^{32} ergs/s. Thus 2.4×10^{33} ergs/s are radiated into ν_H's. Such a radiation rate is marginally acceptable/unacceptable; modifications, such as decreasing slightly the rise in temperature as one approaches the center of the collapsed core, would lower this rate considerably.

Laboratory constraints arise from experiments on ν_e disappearance. The predicted $\sin^2(2\theta)$ for ν_e disappearance is 10^{-2}, while the experimental bound [16] is 7×10^{-2}.

As discussed earlier, these ideas may be extended to involve the other light neutrinos. Whether there is a single ν_H mixing with neutrinos from each family or each family has its own ν_H, all the previous discussions and limits apply. In addition, the ν_μ-disappearance results [17] place a limit on the mixing of this neutrino with ν_H of $(\xi_{\nu_\mu})^2 < 0.02$. Should ν_H couple both to the electron and to the muon neutrinos, it would induce a $\mu \to e\gamma$ transition. We may estimate the branching ratio for this process,

$$B(\mu\to e\gamma) \approx \left(\frac{\alpha}{\pi}\right)\left(\frac{m_{\nu_H}}{m_\mu}\right)^{2}(\xi_{\nu_e}\xi_{\nu_\mu})^2 \approx 10^{-12}\xi_{\nu_\mu}^2, \qquad (7)$$

which is well within present bounds [18].

We have presented a mechanism for a "rapid" decay of the hinted-at 17-keV neutrino that involves no hypothetical particles other than those already postulated for other reasons. The DFSZ axion scheme involves a singlet Higgs meson, the χ, whose only purpose was to make f_a large; we have provided it with another *raison d'être*, namely, that of giving ν_H its mass.

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